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THE X-33 PROGRAM, PROVING SINGLE STAGE TO ORBIT

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by

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ABSTRACT

The X-33, NASA's flagship for reusable space plane technology demonstration, is on course to permit a crucial decision for the nation by the end of this decade. Lockheed Martin Skunk Works, NASA's partner in this effort, has led a dedicated and talented industry and government team that have met and solved numerous challenges within the first 26 months. This program began by accepting the mandate that included two unprecedented and highly challenging goals: 1) demonstrate single stage to orbit technologies in flight and ground demonstration in less than 42 months and 2) demonstrate a new government and industry management relationship working together with industry in the lead.

During 1997, critical design reviews were conducted and these elements went into fabrication and test. The flight liquid oxygen tank was the first major element to complete final assembly. This tank was delivered to the Skunk Works assembly area in early February 1998. The liquid hydrogen tanks are currently in final assembly and testing and will be delivered to vehicle assembly in the next few months. Another new technology element of the X-33, the aerospike engine is an engine concept that has never been flown, but has been extensively ground tested. While the aerospike engine will be flown for the first time on the X-33, it is a marriage of both heritage and advanced technology components. The aerodynamic shape of the X-33 and the follow on single stage to

orbit is referred to as a lifting body. The lifting body shape has been studied and even flight tested over the past several decades, however this particular incarnation of the shape will be the first ever subjected to hypersonic flight conditions.

X-33 space plane flight tests are to be conducted in an unprecedented manner: takeoff from the Edwards Air Force Base in California to two landing sites in Utah and Montana. Since this is the first overflight of populated areas of the US by a rocket powered space plane, NASA decided to prepare an Environmental Impact Statement (EIS). In October 1997, the final EIS was released within one year and is precedent setting for an EIS, particularly for a program of this complexity. With this milestone achieved, construction of the prototype spaceport proceeded and is nearing completion. It will be completed by October 1998.

Major X-33 flight hardware has been tested, delivered, and assembly of the vehicle is well underway in anticipation of its flight test program commencing in the summer of 1999. The decision to proceed with a Single Stage To Orbit as a commercial venture is expected in the fall of 1999.

BACKGROUND

The US Presidential Decision Directive - "National Space Transportation Policy" - dated August 5, 1994, chartered NASA to pursue reliable and affordable access to space, to lead the technology development and demonstration of the next generation reusable space transportation system, and to focus the research on technologies for a sub-scale flight demonstration which would prove the concept of Single-Stage-To-Orbit (SSTO).

NASA's assigned responsibility for the next-generation reusable technology development/demonstration program led to a decision in July 1996 by the President to proceed with the development and flight demonstration of a sub scale X-33 vehicle which would prove the concept of SSTO. This decision was the first of two major X-33 decisions directed by the National Space Transportation Policy. This first decision was made based on specific programmatic, business planning and technical criteria as described in the 11-point Program Management Approach previously approved by NASA, the Office of Management and Budget and the Office of Science and Technology Policy. The second major decision point will be at the turn of the century after X-33 ground and flight tests, when government and industry will consider whether private financing of the development and operation of a full-scale operational reusable space plane should be pursued.

An X-33 Phase II competitive solicitation, Cooperative Agreement Notice (CAN), was released April 1, 1996 for design, development and flight demonstration of the X-33. Selection of one concept and industry partner, Lockheed Martin Skunk Works (LMSW), was completed and X-33 Phase II award was announced July 2, 1996 by the Vice President of the United States.

Program Objectives

The goal of the X-33 program is to demonstrate SSTO technologies and operations concepts that could reduce space transportation costs to one tenth of their current level.

The primary objectives of the X-33 Program are to: 1) mature the SSTO technologies required for a next-generation system, 2) demonstrate the capability to achieve low launch cost and rapid launch turnaround times, and 3) reduce technical and programmatic risks sufficient to encourage private financing of the development and operation of the next-generation system.

The X-33 objectives are to generate the best business arrangement for industry, government and users. The critical parameters include minimum government investment, minimum industry negative cash flow, satisfactory internal rates of return (IRR) and lowest payload to orbit cost. The X-33 program will pursue the best overall solution to these parameters through joint industry, government, user and financial community involvement.

Program-Level Requirements

The top level X-33 Program-Level requirement consists of a flight and ground technology demonstration program that results in a decision to proceed with a reusable space plane. Lower tier program requirements are grouped as follows: 1) Demonstrate Operations Concept - Operations touch labor of less than 50 people, master measurement list of elements requiring in flight monitoring, decision tree of automated vs. ground oversight functions, meet schedule and cost commitments; 2) Demonstrate Commercial Potential - Management approach, calibration of cost estimating and schedule performance 3) Demonstrate Relevancy of Design Methods - SSTO feasibility, system response to combined environ-

ments, validation of vehicle hypersonic flight environments during ascent and reentry lifting body and aerospike engine flight performance.

Program Elements

The X-33 is an integrated technology effort to demonstrate key SSTO technologies, and deliver advancements in: 1) propulsion, including critical elements of the full scale operational engine; 2) lighter, reusable cryogenic tanks; 3) application of New Millennium micro electronics for vastly improved reliability and vehicle health management; 4) advanced thermal protection systems to reduce maintenance; and 5) ground and flight operations techniques that will substantially reduce operations costs for the next generation reusable space plane system.

An integrated ground and flight test program has been implemented to characterize key component technologies and to validate their systems' capabilities both from a performance and an operations viewpoint. The ground-based portion of the program includes reusable cryogenic tanks, composite primary structures, advanced durable thermal protection system, advanced propulsion, advanced avionics and vehicle health management techniques. The X-33 will combine its results with the complementary ground technology advances to reduce the technical risk of privately financing the development and operation of the next generation reusable space plane system.

The X-33 is part of a larger effort to reduce launch costs. The effort is composed of at least three parts, which are believed to be collectively sufficient to substantially reduce costs. The first is that reducing operations costs offers the largest opportunity to reduce launch costs. Second, a reusable single stage to orbit

offers a vehicle with the best promise of enabling reduced operations costs. Finally, a private commercially funded organization offers the most likely chances of executing the reduction of launch costs with a reusable single stage to orbit vehicle.

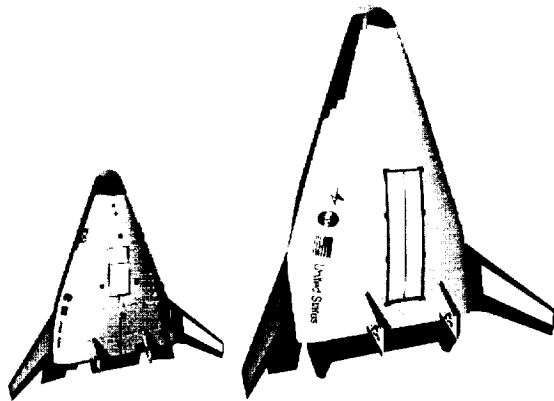
The X-33 is an experiment to reduce the risk of pursuing and validating those three concepts. The X-33 is a subscale model of a reusable single stage to orbit vehicle. It is designed and operated by an industry government team that is led by the industry partner. The X-33 is expected to begin flight test in 1999, and will be conducted out of Edwards Air Force Base in California.

The industry partner, Lockheed Martin Skunk Works, LMSW, leads an integrated team of corporate and government organizations. With the concurrence of the NASA X-33 program manager and the LMSW X-33 program manager the X-33 will be approved for flight. Flight approval is predicated on satisfactory certification of airworthiness, operational procedures and receiving permission to launch and land. The commander of Edwards Air Force Base will grant flight operations permission. The commander will permit operations if X-33 is judged to pose no greater public risk than commensurate experimental air vehicles. The specific procedures are described in a range safety document approved by the commander in March of this year.

X-33 **A STEPPING STONE TO** **VENTURESTAR®**

Designated the X-33, the Skunk Works developed a prototype design of VentureStar® which is one-half the size, one-tenth the weight and one-fourth the development cost. The objective set forth in the X-33 design was to provide full traceability to the full-scale vehicle.

The X-33 is an exact replica of scaled down to a 2-engine vehicle and sized in accordance with the thrust level of the J-2S Linear Aerospike Engine (203 thousand pounds each). The result is a 53% scale vehicle with a GLOW of 273 thousand pounds. The X-33 and VentureStar® are compared in Figure 1.



	X-33	VentureStar®
Weight	273 Klb	2.2 Milb
Length	67ft	127ft
Payload (100 nmi/28.5°)	N/A	50,000 + lb
Payload Bay Size	5 x 10ft	15 x 45ft
Propulsion	2—J-2S Aerospike	7—RS2200 Aerospike

Figure 1. X-33 to VentureStar® Comparison

A structural inboard profile of the X-33 vehicle is shown in Figure 2. Cryogenic tanks designed with multi-lobes to provide high packaging efficiency dominate the internal volume. The liquid hydrogen (LH₂) tanks are graphite epoxy composite; however, the liquid oxygen (LOX) tank is 2219 aluminum inasmuch as there were no composite materials which are compatible with LOX at the beginning of this phase of the Program. The cryogenic tanks are an integral part of the load carrying structure in the X-33, which is fully traceable to VentureStar®. All of the primary interconnect structure, including the thrust structure, is made of lightweight graphite ep-

oxy composite material as well. The outboard canted and inboard vertical fins are made of titanium, except for the leading edges, which are carbon-carbon.

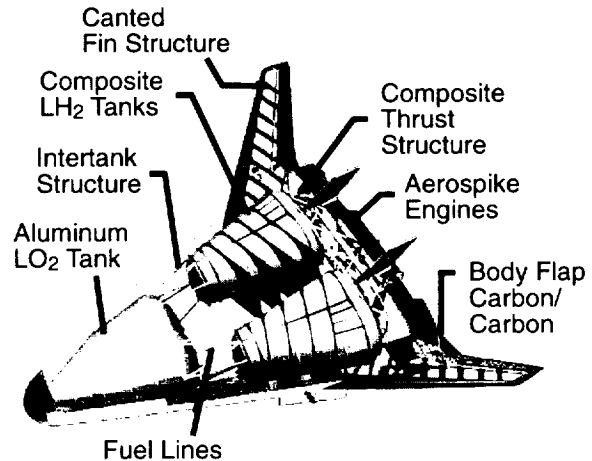


Figure 2. X-33 Structural Inboard Profile

The X-33 is being assembled by a Skunk Works manufacturing team in an aircraft hangar in Palmdale, California. Assembly tooling is 90% complete and many elements of the X-33 have been placed in the assembly fixture as shown in Figure 3. The LOX tank is shown positioned in the assembly fixture and support structure is being put in place to attach the external thermal protection system, which will complete assembly of the forward one-third of the vehicle. Aft of the LOX tank, cradles are being built for placement of the LH₂ tanks when they are delivered later this year. Behind the LH₂ tanks, the base of the vehicle, or thrust structure, has nearly completed assembly. Vehicle subsystem (avionics, environmental controls, actuators, landing gear, etc.) deliveries will be complete in January 1999 and these components are being installed in accordance with the assembly sequence. Assembly will be complete when the linear aerospike engines are delivered, attached to the thrust structure, and hooked up to the main propellant system in May of 1999.

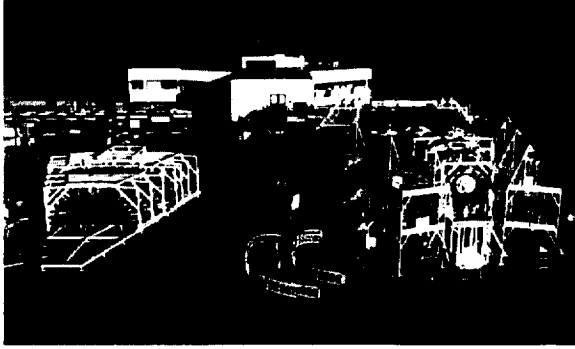
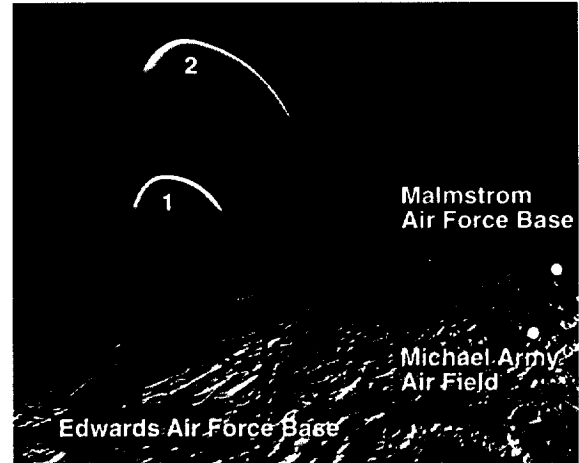


Figure 3. X-33 Assembly

Flight test of the X-33 is planned to take place over land in the western United States. The ability to do this is provided by a higher level of designed-in redundancy and reliability compared to other rocket designs. The X-33 is being designed to accommodate an engine failure and still complete its mission. The avionics are triplex and flight controls are dual redundant. The X-33 requirement for reliability is less than 1 failure in 100 flights.

As with most prototype programs, an incremental flight envelope expansion approach will be used to minimize risk. Narrow flight corridors over lightly populated areas have been defined to minimize the overflight approval issues for the Environmental Impact Statement. The launch site is Edwards Air Force Base in California. Landing sites are at Michael Army Air Field in Utah (450 miles range), and Malmstrom Air Force Base in Montana (950 miles range). The characteristics of the flight trajectories are shown in Figure 4.



Flight Profile 1	Flight Profile 2
Mach 9	Mach 13.8
165,000ft (31 miles high)	300,000ft (57 miles high)
Engine Cutoff: 175 seconds, 100 miles from takeoff	Engine Cutoff: 195 seconds, 140 miles from takeoff
Land: 450 miles, 14 min	Land: 950 miles, 24 min

Figure 4. Expanding the X-33 Flight Envelope

The X-33 launch site is being built in a remote area of Edwards Air Force Base encompassing approximately 50 acres. Groundbreaking ceremonies were held on November 14, 1997 following the Environmental Impact Study Record of Decision signing on November 4. Only 30 of the 50 acres are being disturbed to minimize impact to the environment. All Desert Tortoises and Joshua Trees were transplanted outside a fenced compound in accordance with the EIS. Elements of the launch site include the vehicle pad and erection mechanism, flame trench, cryogenic storage tanks (hydrogen, oxygen, nitrogen and helium), tower to supply water for sound suppression, a translating hangar on rails to shelter the X-33 in the horizontal position for maintenance and pre-launch preparation, and an Operations Control Center on Haystack Butte tied to the launch site by fiber optic and telephone cables. A photograph of the launch site is shown in Figure 5.

The X-33 will be flight tested in 1999. A total of 15 flights are planned. Within the flight envelope expansion process, a total of seven design missions are planned to accomplish the technology demonstration objectives. This approach provides a robust flight program with more than double the number of flights in the program than are required to accomplish the basic flight objectives. To accomplish the design missions, 5 flights to Michael Army Airfield, and 2 flights to Malmstrom Air Force Base are required. This leaves a total of eight unallocated flights to assure accomplishment of the program objectives. The flight demonstration program objectives are to:

- Demonstrate aircraft-like reusability, maintenance and scheduling by flying one (1) two-day turnaround flight and two (2) consecutive seven-day turnaround flights.
- Measure surface catalysis caused by atomic oxygen.
- Measure boundary layer transition.
- Achieve thermal protection system multi-use operating limits.

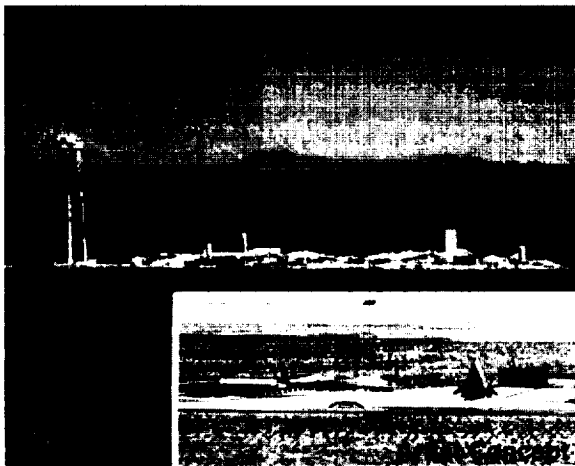


Figure 5. X-33 Launch Site

The flight test program is structured to achieve maximum risk reduction in critical technology areas. The speed and altitude test matrix

provides a realistic simulation of the reentry thermal environment permitting validation of the reusable metallic thermal protection system. External aerodynamic and propulsion integration characteristics of the X-33 are the same as for validating flight characteristics and controllability as well as integrated propulsion efficiency and thrust vectoring capability. Liquid hydrogen tanks will be of lightweight quad-lobe graphite epoxy composite material that are designed to carry structural loads and contain LH_2 . Autonomous flight management will be demonstrated through launch, entry, approach and landing, rollout, and post landing operations. The ability to turn the X-33 around for reflight in less than a week will demonstrate the built-in reliability and aircraft-like operational efficiency of the concept. An artist's rendering of the X-33 in flight is shown in Figure 6.

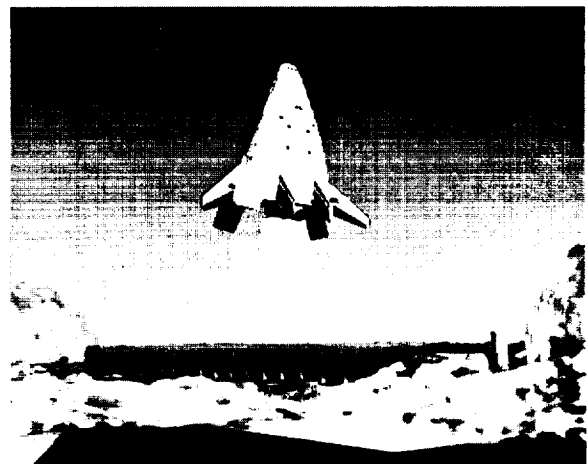
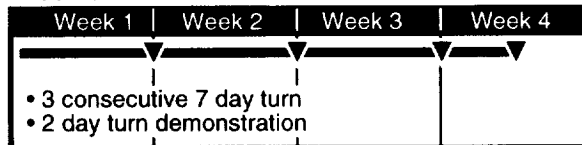


Figure 6. Artists Rendering of the X-33 in Flight

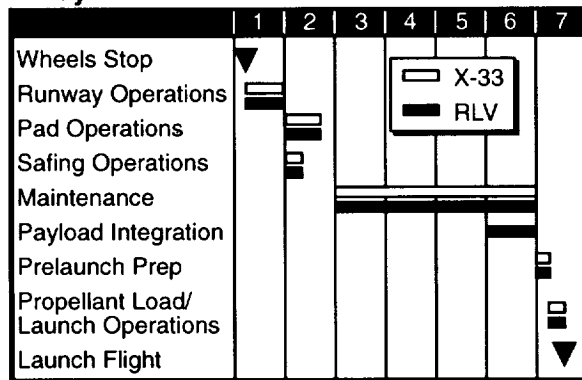
The X-33 is designed to be maintained and operated like an airplane. A critical enabler for this operational efficiency is the robust, durable, all-weather metallic thermal protection system that requires only inspection and spot replacement of 18-inch diamond shaped panels wherever there may be damage. Maintenance is facilitated by a fully integrated ve-

hicle health management system to pinpoint problems. The timelines for a standard 7-day and an accelerated 2-day turnaround from landing to relaunch are shown in Figure 7 with all of the critical operations and time spans highlighted.

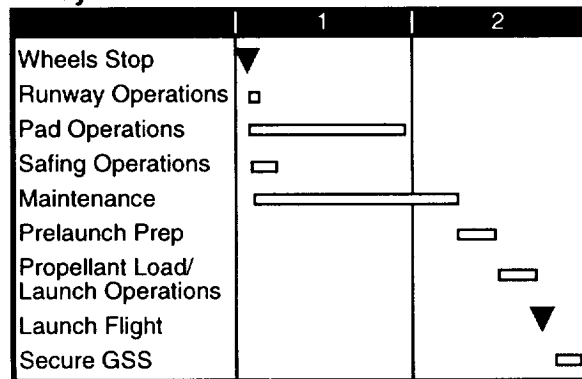
X-33 Turnaround Demo



7 Day Turnaround



2 Day Turnaround



Operations focusing on turnaround activities

Figure 7. Landing to Relaunch Cycle Time

X-33 Ground Operations

A major objective of the X-33 Program is to demonstrate operations that can be traceable to VentureStar®. Validation of the X-33 operations concept will enable VentureStar® Spaceport operations as illustrated in Figure 8. This is an innovative “runway-to-pad-to-orbit” concept that contains the least possible site infrastructure. The Ground Support System requires the lowest investment and facilitates the most rapid turnaround timelines. A translating hangar at the launch pad provides weather protection and allows all vehicle processing to be accomplished at the pad. The system employs an interchangeable Payload Canister System that eliminates the requirement for a clean room environment for payload integration. The X-33 will fully demonstrate this operational concept except for payload processing.

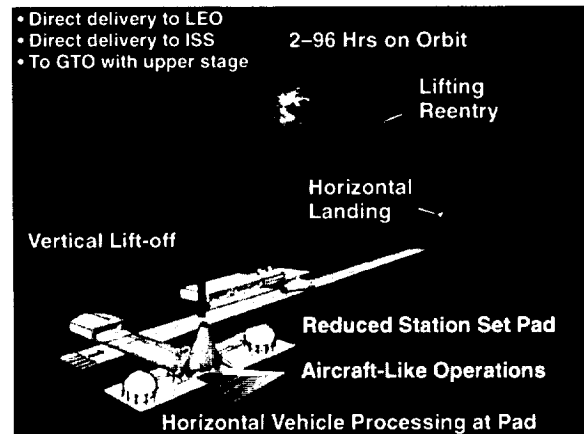


Figure 8. VentureStar® Operations Concept

THE VENTURESTAR® PROGRAM PLAN

The program schedule is shown in Figure 9. Phase I was a competitive phase that concluded June 30, 1996. An industry team led by Lockheed Martin and NASA are now executing Phase II that will conclude by the end of the year 2000. A parallel SSTD RLV technology development program began mid-1997 and will conclude in 2000. Technology development will complement the X-33 flight test by focusing on a composite liquid oxygen tank development and full-scale prototype engine for VentureStar®. Success of X-33 flight tests and the SSTD RLV technology development will enable a decision to proceed with development beginning in 2000. Flight testing of VentureStar® will occur in 2004, and the vehicle will be introduced into revenue service later that year.

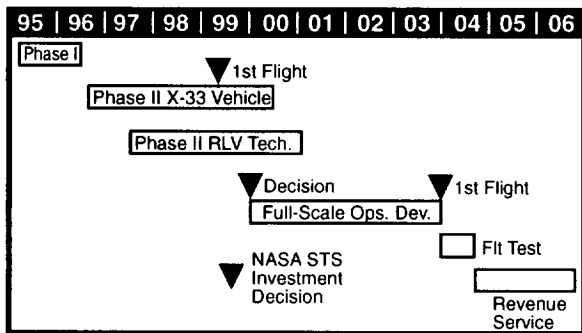


Figure 9. Baseline Program Plan

VentureStar® is a commercial program that will require a business plan that promises financial returns sufficient to attract investment in a multi-billion dollar development. The business plan needs to demonstrate that program technical, cost, financial and market risks have been reduced to a point where there is a high degree of confidence in achieving program objectives. The X-33 flight test and SSTD RLV ground technology demonstrations will reduce program technical risk to acceptable levels, and the cost of executing the X-33 pro-

gram provides traceability to development of the full scale VentureStar®. X-33 is also providing lessons learned to design a VentureStar® vehicle that is volumetrically more efficient, aerodynamically improved, and well balanced without ballast. The single-stage-to-orbit capability and aircraft-like operating characteristics enable a frequent launch rate of at least 20 flights per year per vehicle at attractive launch prices allowing a significant share of the addressable market to be captured. All of these elements combine to create a business plan that promises attractive rates of return on investment. Figure 10 is a pictorial presentation of how these elements fit together to support VentureStar® development leading to commercial launch operations in 2004.

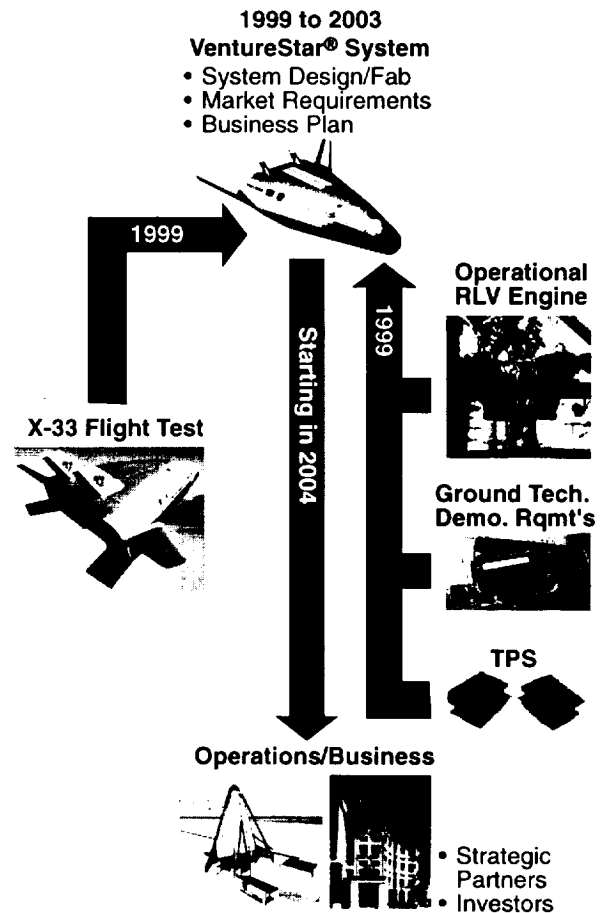


Figure 10. X-33 to VentureStar® Transition

Robert Anson Heinlein has often been quoted: “Reach low orbit and you’re halfway to anywhere in the Solar System”. It can also be said that reaching low Earth orbit at a fraction of today’s costs, opens a Universe of possibilities.

